# CRACK GROWTH-BASED FATIGUE-LIFE PREDICTION OF ADDITIVELY MANUFACTURED MATERIALS

MohammadBagher Mahtabi[1*], Aref Yadollahi[1], James C. Newman Jr[2]

[1]*University of South Alabama, Mobile, AL, USA*
[2]*Mississippi State University, Mississippi State, MS, USA*
** Presenting Author email: mbmahtabi@gmail.com*

## Abstract

In this study, a plasticity-induced crack closure model, FASTRAN, was used to predict the fatigue life of Inconel 718, 17-4 precipitation hardening (PH) stainless steel (SS), and Ti-6Al-4V alloys fabricated via additive manufacturing (AM) systems. Results indicated that in the presence of large defects (e.g., lack-of-fusion defects), the total fatigue life of AM specimens is dominated by crack growth. Results indicated that variations in the fatigue lives of specimens in machined and as-build surface conditions can be predicted based on the characteristics of AM process-induced defects and surface profile. Effect of build orientation on fatigue life was also captured based on the size of defects projected on a plane perpendicular to the loading direction. In addition, maximum valley depth of the surface profile can be used as an appropriate parameter for the fatigue-life prediction of AM specimens in their as-built surface condition.

## 1. Introduction

The key challenge confronting further adoption of metal AM by highly regulated sectors such as the aerospace and energy industries is qualification and certification of fabricated parts in applications in which the consequence of failure is high. Thus, fatigue life assessment of metal AM parts, is of major concern and must be addressed to fulfill the operational requirements and certification constraints for fatigue- and fracture-critical applications. Fatigue behavior of AM metallic materials is dominated by process-induced defects—such as gas-containing pores and lack-of-fusion (LOF) defects. Despite significant research efforts on AM process optimization and control, producing a defect-free AM part has not been achieved yet. The major concern in the fatigue-life description of AM parts is a large amount of scatter and uncertainty, mostly due to the existence of process-induced defects and their variations in size, location, and spacing. Thus, the first step toward qualification and certification of AM part is to understand and model the influences of defect characteristics (including size, location, and spacing) on fatigue performance.

The purpose of this paper is to use the crack growth approach for the fatigue-life prediction of AM materials, including Inconel 718, 17-4 PH SS, and Ti-6Al-4V alloys. Effective stress intensity factor as a function of crack-growth rate was obtained from testing g compact tension, C(T), and modified (nonstandard) compact, MC(T), specimens. The plasticity-induced crack closure model, FASTRAN, was used to predict fatigue lives for the specimens in different conditions based on the characteristics of process-induced defects and surface profile. Predicted fatigue-life results were compared with the experimental fatigue-life data. The initial crack size was obtained from the defects' area projected on a plane perpendicular to the load direction, as the actual initial flaw size (AIFS). The concept of equivalent initial flaw size (EIFS) was also used to consider some features that may be missed in the life-prediction code.

## 2. Results

Schematics in Figure 1A show the measuring method for the crack initiation size in our crack growth-based fatigue modeling. The crack-growth rate data, $dc/dN$, versus effective stress-intensity factor range, $\Delta K_{\mathrm{eff}}$, obtained from the experimental tests are provided in Figures 1B-C. The baseline $\Delta K_{\mathrm{eff}}$-rate curves were obtained from large-crack-growth tests. Predicted fatigue lives using FASTRAN as well as the experimental fatigue data are shown in Figures 1D-E. As can be seen in Figure 1D, the predicted fatigue curves based on real initial flaw size (RIFS) for 17-4 PH SS do not agree well with the test data, and the calculated fatigue lives are overestimated, especially at higher stress levels (i.e. LCF). The reason for over estimation of fatigue lives using RIFS may be related to the presence of a large number of LOF defects in the fatigue specimens. Having numerous large size voids provides the opportunity of crack growth from several location and their coalescence reduces the residual strength of specimen, leading to shorter fatigue life. Fatigue life calculation based on the EIFS fits the experimental fatigue data quite well. By using the EIFS, which has a larger size than RIFS, the effect of other involving features, such as defect interactions, can be taken into account in the estimated fatigue-lives. For the Inconel 718 specimens, the predicted fatigue curve using the RIFS agreed well with the test, as seen in Figure 1E. Using the size of largest and smallest detected voids that served as crack initiation sites, lower and upper bounds were determined and variations in fatigue life of Inconel 718 specimens were accurately estimated.

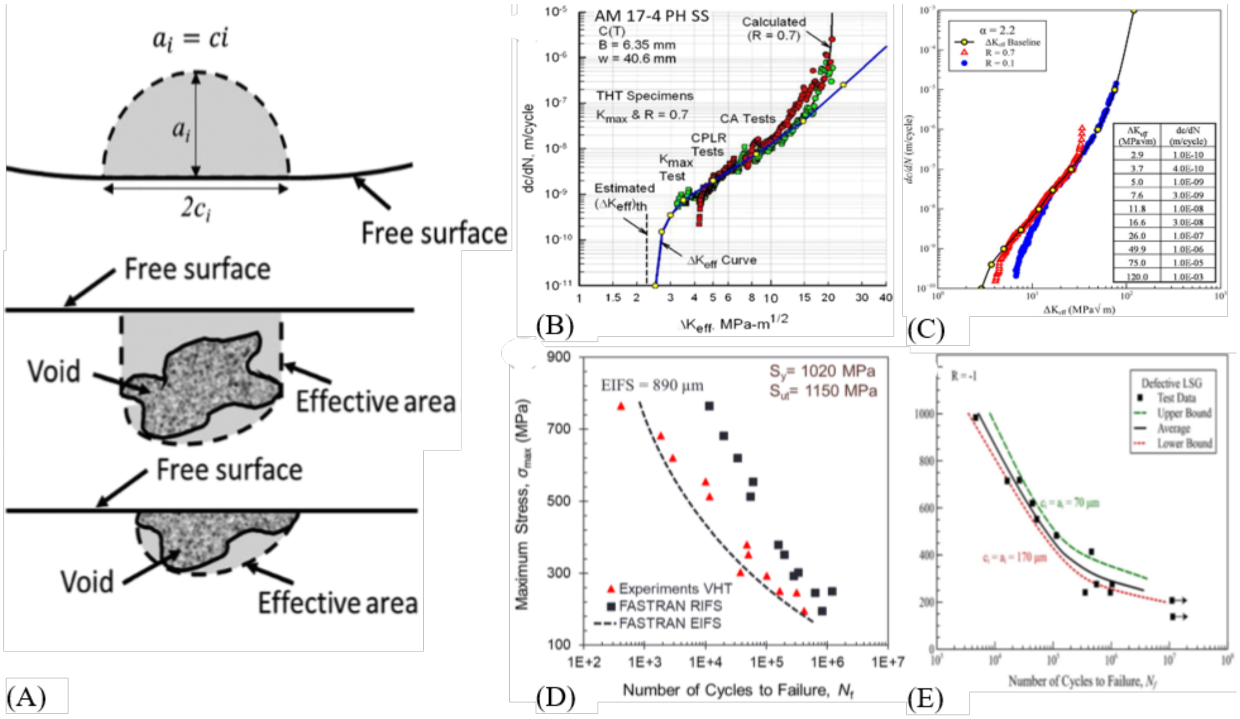

Figure 1– (A) Schematic showing the geometry of the cracks in fatigue modeling as well as the effective areas for an irregularly shaped void used in fatigue-life calculations; (B-C), experimental fatigue crack-growth rate data, and (D-E) experimental and calculated fatigue lives using FASTRAN for AM 17-4 PH SS and Inconel 718 specimens, respectively.

## 3. Conclusions

According to the results obtained in this study, fatigue-life prediction based on the crack growth approach can be considered as an efficient and reliable method for the current state of AM, in which the formation of process-induced defects cannot be avoided. In the presence of large voids (i.e. LOF defects), total fatigue life of AM materials is dominated by crack growth. Fatigue modeling results indicated that effect of build orientation on fatigue life of AM materials can be captured based on the size of defects projected on a plane perpendicular to the loading direction. Knowing the statistical range of the void size, variations in fatigue life of AM specimens can be accurately captured using a crack closure-based fatigue crack growth model.

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